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Deuterium in-vessel retention characterisation through the use of particle balance on Tore Supra

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Abstract

Fuel retention inside plasma facing components will be a crucial issue not only in fusion reactors of the future, but also in ITER. The estimation of the fraction of the fuel which remains trapped inside the vessel is quite a difficult task. Particle balance analysis provides information for the whole vacuum chamber as a function of time and can be use to monitor the tritium in-vessel retention in real-time. On Tore Supra with a careful choice and position of pressure sensors, proper calibration procedures, the accuracy of the balance is around 10%. Particle balance analysis have been performed on many long pulse discharges and deuterium in-vessel retention has been found to be a constant around 5×10^{20} D/s after several minutes of plasma. The evolution of the retention rate with plasma parameters indicates that deuterium bulk implantation and diffusion could dominate codeposition with carbon atoms. Particle balance is a powerful tool that should be implemented in ITER.

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Keywords: Particle balance; Deuterium inventory; Retention; Gas injection and fueling; Tore Supra

1. Introduction

Fuel retention inside plasma facing components (PFC) will be a crucial issue not only in fusion reactors of the future, but also in ITER. Indeed, the use of tritium requires careful monitoring all along its cycle. In addition, for safety reasons, the tritium in-vessel inventory will be limited and this limitation has to be considered for the choice of the material of the first wall.

The estimation of the fraction of the fuel which remains trapped inside the vessel is quite a difficult task. Post-mortem analysis of PFC elements using different methods (thermo-desorption, NRA, NMR) can give accurate information on retention [1] but these measurements are localised, integrated over plasma operations (with sometimes very different plasma configurations), require vessel venting, some component may not be accessible and bulk material measurements remain problematic.

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Therefore, extrapolation to the whole vacuum chamber and prediction for ITER are somewhat hazardous.

Particle balance analysis, on the contrary, provides information for the whole vacuum chamber as a function of time [2]. In principle, it can be used to monitor the in-vessel tritium retention in real-time. However, the estimations of the particle input on the one side and of the particle exhaust on the other side are often not accurate enough to perform a valid subtraction and obtain the wall inventory. Nevertheless, with a careful choice of sensors, proper calibration procedures, and when dealing with substantial retention rate (few % of the injected flux), particle balance may become very helpful.

In the first part of this paper, the method used in Tore Supra to perform the particle balance will be described in details including a discussion on the error. The second part of the paper will deal with the results obtained on deuterium retention with this method on Tore Supra. Different plasma scenarios have been investigated in order to find the main influencing factors.

2. Particle injection and exhaust accuracy on Tore Supra

Particle input is measured at the gas reservoir level which is typically at 1.3 bar at the beginning of a pulse. The volume of each reservoir (~2 l) has been measured with an estimated accuracy of 2%. Pressure drop is monitored by two different gauges, a 100 mbar differential capacitance manometer for small injections (<20 Pa m^3, accuracy ~0.05 Pa m^3) and a 2 bar absolute piezoresistive transmitter for large injections (<260 Pa m^3, accuracy ~0.5 Pa m^3). The gas reservoirs which are at different distance from the baked vessel are equipped with thermocouple in order to take into account the temperature in the estimation of the amount of injected particles. The estimated accuracy for gas input is 3%.

Tore Supra is equipped with a toroidal pumped limiter (TPL) located at the bottom of the vacuum vessel [3]. A fraction of the SOL plasma is neutralised onto 12 dedicated carbon tile sets just beneath the limiter and pumped throughout ducts by turbo-molecular pumps. Ten of the ducts are equipped with a 2 m^3/s turbo-molecular pump and two high accuracy absolute pressure sensors, one in the vertical port and the other at the pump, while two ducts are reserved for optics diagnostics. Capacitance manometers (1.3 Pa ± 0.12%) have been chosen because they are insensitive to the type of gas and have a linear response to pressure. In parallel, for torus evacuation, a pumping unit is connected to the vessel in the mid-plane by a duct and is constituted by three turbo molecular pumps $(2\times 2.2\ \mathrm{m^3/s} + 1\times 5\ \mathrm{m^3/s})$. The pressure in the vicinity of these pumps is also monitored by a capacitance manometer. Finally, the LHCD system has a turbo-molecular pump (2 m^3/s) that is connected to the vacuum vessel through the Launchers located in the mid-plane. Therefore, with pressure measurements in the torus mid-plane and inside the bottom limiter pumping ducts, it is possible to work out the particle exhaust of the turbo-molecular pumps: $\phi_{\mathrm{TMP\ exhaust}} = \sum_{i=1}^{14} P_i S_i$, i being the pump number, P_i the measured pressure in the vicinity of pump i and S_i the effective pumping speed of pump i.

In order to improve the confidence in the determination of the exhaust, capacitance manometers have also been installed at the roots pumps level (two units) where the particles coming from all the turbo-molecular pumps (TPL, vessel and LHCD) are collected. The pressure at the roots level is an order of magnitude higher than at the turbo-molecular pumps level and thus a second independent estimation of the exhaust is available.

To determine the turbo-molecular pumps exhaust, an effective pumping speed is determined for each turbo-molecular pump. This effective speed, due to pressure gradient in the duct, depends on the distance between the pump and the pressure gauge used to compute the flux. Dedicated pulses without plasma with several stabilized pressure steps are performed to work out the effective pumping speeds as a function of the pressure. One of these pulses is shown in Fig. 1. The speed is adjusted so that the extracted flux matches the injected flux during each step. The integral of the extracted flux

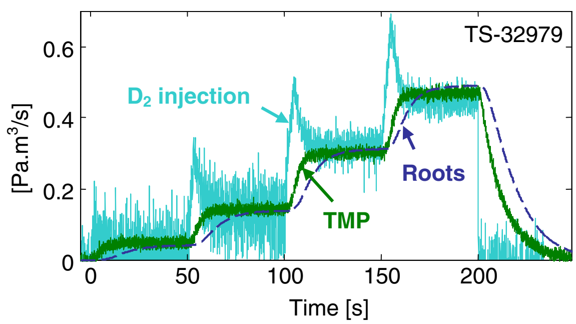

Fig. 1. Gas balance calibration pulse (TS#32979). Time evolution of the deuterium injection, estimated TMP and roots exhaust fluxes.

is also compared to the total amount of injected particles. It has to be noted that the resulting effective speed accuracy relies on the gas injection accuracy and is highly dependent on the pressure measurement. Errors on pressure sensor calibration are thus compensated in the worked out effective pumping speed. The effective pumping speed is found to be not very sensitive to pressure and similar for all the TPL pumping ducts. Therefore for sake of simplicity a constant value is used for all the TPL turbo pumps ($S = 1.8\ m^3/s$). Taking into account this choice the overall accuracy for the flux extracted by the turbo-molecular pumps is estimated around 10%. This value could be substantially improved by using individual pumping speed (one calibration pulse/TPL pump) and a weak pressure dependence for the pumping speed.

Besides, the flux extracted by the roots is computed using pressure measurements and manufacturer pumping speed curves. In that pressure range, the pumping speed is highly dependent on the pressure: $\phi_{\text{roots exhaust}} = \sum_{i=1}^{2} P_i S_i(P_i)$. A very good agreement is found between root exhaust and particle injection (see Fig. 1). For this measurement, the accuracy relies also mainly on the pumping speed and is estimated to be around 5–10%. The time constants for pressure equilibration are typically a few seconds at the turbo-molecular pumps and tens of seconds at the roots pumps.

These measurements, either at the turbo pumps or at the roots pumps, are not valid below 1e−4 Pa (capacitance manometer measurement range). To monitor the deuterium release between pulses and overnight, ionic gauges are used. From 1e−4 Pa to the minimum vessel pressure (a few 1e−6 Pa in Tore Supra), the deuterium exhaust determination is much more troublesome. Indeed, the gauges are sensitive to the type of gas whereas the residual gas may be dominated by impurities like hydrogen or nitrogen. Therefore, pressure measurement should be systematically coupled to mass spectrometer analysis. Besides, glow discharge cleanings (GDC) are often operated and the use of deuterium and helium gases makes the analysis even more complex. In addition, over long period, sensitivity drifts of ion gauge and mass spectrometers have been observed which implies that one must regularly calibrate the measurement system, typically once per month. The deuterium release between pulses over a whole campaign has not been yet estimated in detail in Tore Supra. Only rough estimates have been performed based on the extrapolation of a typical day of operation, and the analysis of a few GDC.

3. In-vessel particle retention from particle balance analysis

Particle balance analysis using particle injection and pump exhaust as described in Section 2 has been performed on many plasma discharges in deuterium. The analysis showed that a large fraction of the injected flux remains inside the vessel at the end of the discharge [4,5]. As can be seen in Fig. 2, when the duration of the pulse is longer

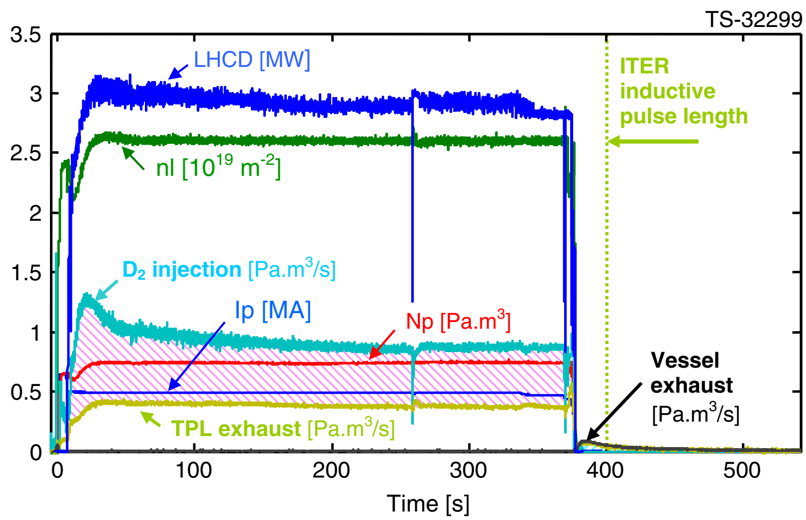

Fig. 2. Particle balance (deuterium injection, TPL and vessel exhaust) and main plasma parameters (plasma current [I_p], lower hybrid power [LHCD], line integrated density [n_l] and plasma particle content [N_p]) for a long pulse discharge in deuterium (TS#32299, 1 GJ discharge). In-vessel retention during the pulse and recovery after the pulse are hatched.

than the time constant of the pumping systems, an apparent in-vessel retention rate can be worked out (typically 0.5 Pa m^3/s–2.5×10^{20} D/s). The measured rate is the sum of different deuterium retention mechanisms: adsorption in porosities, implantation, bulk diffusion and trapping, codeposition with eroded carbon atoms plus a negative contribution from outgassing of in-vessel components:

$$\phi_{\text{in vessel}} = \phi_{\text{adsorption}} + \phi_{\text{implantation}} + \phi_{\text{bulk diffusion}} + \phi_{\text{codeposition}} - \phi_{\text{outgassing}}. \quad (1)$$

The particle release ($\phi_{\text{outgassing}}$) which includes fuel from previous discharges (for instance from different plasma configurations) and also the impurities (intrinsic, from venting, leakage, conditioning, localised heat loads, etc.) is very sensitive to temperature. Therefore it is crucial to have stabilized PFC temperatures to get access to the effective deuterium retention rate. Moreover, the gas pumped has to be analysed in order to take into account the contribution of impurities in the exhaust to properly work out the deuterium retention. In Tore Supra long pulse discharges, mass spectrometer measurements of the pumped flux indicate a low fraction of impurities: a few % of hydrogen and about 1% of hydrocarbons, others impurities being negligible.

A few important features of the in-vessel deuterium retention have been brought to light through the particle balance analysis. Firstly, the retention rate ($\phi_{\text{in vessel}}$) does not saturate, at least for several minutes of plasma, moreover it appears constant after a few minutes. Secondly, the particle recovery after long pulses remains small compared to the amount of particle trapped during the discharge. Thirdly, the retention rate is very reproducible and not sensitive to initial wall conditions provided the vessel is properly conditioned and that the pulse duration is long compared to the duration of current ramp up and ramp down phases. Finally, in the present Tore Supra database, the retention rate exhibits a weak dependence on main plasma

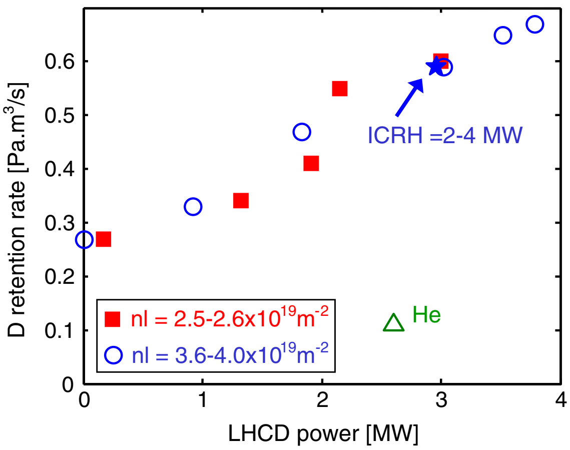

Fig. 3. Deuterium in-vessel retention rate as a function of LHCD power (after 30 s of plasma discharge) for two ranges of plasma densities (line integrated density from 2.5 to 4×10^{19} m^{-2}) and ICRH power. Helium in-vessel retention rate is also reported (triangle).

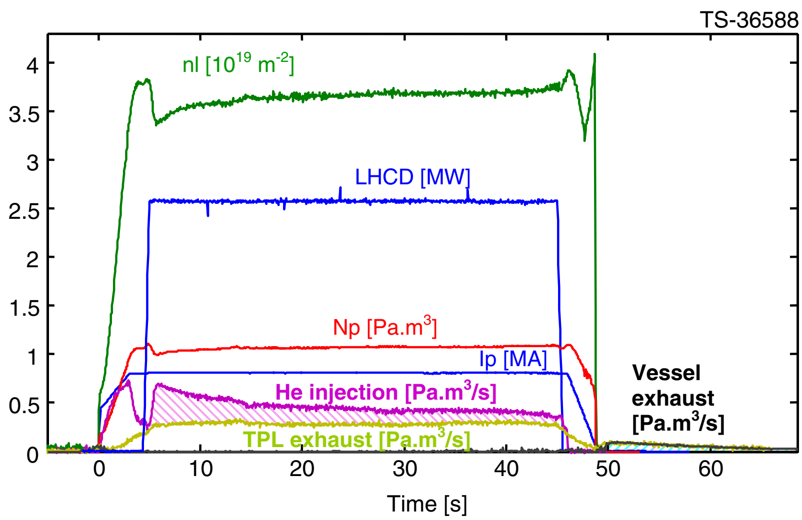

Fig. 4. Particle balance (helium injection, TPL and vessel exhaust) and main plasma parameters (plasma current [I_p], lower hybrid power [LHCD], line integrated density [n_l] and plasma particle content [N_p]) for a long pulse discharge in helium (TS#36588). In-vessel retention during the pulse and recovery after the pulse are hatched.

parameters except LHCD power [6]. The deuterium retention rate has been plotted versus various plasma parameters in Fig. 3. Higher density, higher power regimes are being investigated to extend the database. Pulses at high power (>6 MW) tend to be difficult to analyse, and thus present a larger error on the retention, since the use of ICRH induces localised heats load due to fast particle losses and substantial outgassing. In these pulses, limited in duration by the ICRH system, steady-state conditions for particle balance are rarely met.

Several pulses have been repeated without active pumping and identical retention rates have been worked out pointing out the confidence in the exhaust measurement. In addition, long pulses in helium have been analysed as helium behaviour with respect to retention is very different from deuterium. After 40 s, the wall is still pumping and a retention rate of $\sim$0.1 Pa m^3/s is found as shown in Fig. 4 (five times lower than for deuterium).

4. Discussion and conclusions

As detailed in Eq. (1), the deuterium in-vessel retention computed through particle balance includes many contributions. However, when this rate becomes nearly constant ($t > 100$ s), some contributions should have cancelled. Indeed, adsorption should tend to zero when all open pores are filled by deuterium, implantation should saturate the surfaces while outgassing should become minimal and constant as PFCs reach their steady-state temperature (in pure LHCD discharges). Therefore, at this point retention rely only on two contributions namely codeposition and bulk diffusion. Codeposition was firstly evoked to explain the different features worked out from gas balance analysis and presented in Section 3 [4]. However post-mortem analysis of carbon deposits from the different regions of the vacuum vessel showed that the deuterium content was small and not able to account for all the trapped deuterium [5]. Particle balance does not allow for a direct distinction between codeposition and bulk diffusion however the changes in retention rate observed in different plasma configurations might give some further insight. The small change in the retention rate with important change in recycling flux of deuterium and carbon (factor two in high density discharges) could indicate that the codeposition is not dominant. Besides, the influence of LHCD that could be attributed to power losses into the scrape of layer (a few %), could be related to an enhanced implantation and diffusion mechanisms due to higher ion energy. Besides, it has been observed in laboratory that the retention in graphite, still below Tore Supra level, increases with the energy of the impinging ion (by a factor 3 between 25 eV and 1 keV [7]). Finally, the dynamic retention found in helium discharges might indicate that, as there is no codeposition with helium, bulk implantation and diffusion could be enhanced by the high fluence and/or defects, cracks, channels, etc. inside the bulk beneath the CFC surface.

In ITER, for safety reasons the real-time monitoring of the in-vessel tritium inventory will be mandatory. Retention rate of the magnitude of Tore Supra, 50% of the injected particles, would limit drastically the number of pulses without the use of efficient detritiation techniques between pulses. As shown here, the particle balance could give access to the in-vessel inventory, in particular during long pulses, with a reasonable accuracy. Therefore, a set of dedicated pressure measurements should be implanted in ITER. As ITER discharges will last for hundred of seconds, small tubes could connect remote sensors to regions of interest (time constant of tens of seconds acceptable). To avoid conductance and plasma configuration issues [8], neutral pressure should be measured as close as possible of the different pumps. In addition, comparison of particle exhaust during pulses with cryo-pumps release would allow for the estimation of the contribution of outgassing between pulses and overnight with a good accuracy. Thus, the particle balance could play a significant role in the first hydrogen phase of ITER in order to quantify the retention rates during the different phases of the discharges and could allow for the validation of tritium retention models.

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